

Probing the electroweak sector at DØ with WW production and other diboson final states

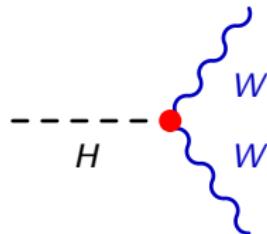
Émilien Chapon
on behalf of the DØ Collaboration

CEA Saclay / Irfu / SPP

Joint Experimental-Theoretical Physics Seminar
May 31th, 2013



Once Upon A Time... (A Tale of the Standard Model)



$$\mathcal{L}_{EW} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\text{Tr}[W_{\mu\nu}W^{\mu\nu}] + (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi)$$

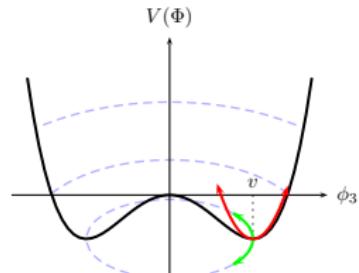
Electroweak symmetry breaking mechanism

Let there be Φ a SU(2) doublet such that

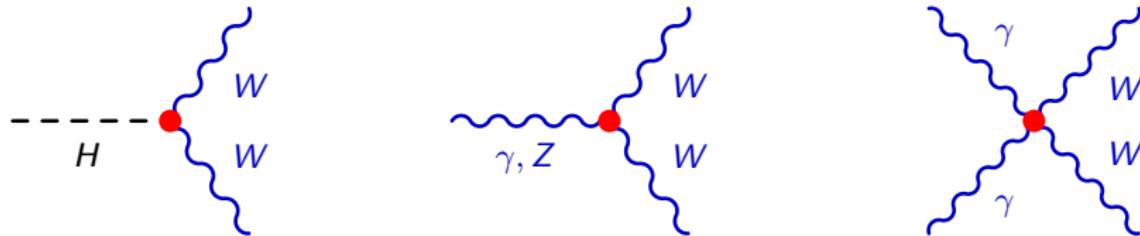
$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4.$$

→ Massive weak gauge bosons.

$$M_W = \frac{1}{2}v g_2, \quad M_Z = \frac{1}{2}v \sqrt{g_1^2 + g_2^2}, \quad M_A = 0$$



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Multiple gauge boson couplings

$SU(2)$ is non-abelian.

→ Triple and quartic gauge boson couplings.

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon^{abc} W_\mu^b W_\nu^c$$

Outline

1 Search for the Higgs boson in the WW channel [1]

- Analysis overview
- Hunting down the Higgs boson
- Results

2 Anomalous quartic gauge couplings [2]

- Theoretical framework
- Data and MC samples
- Analysis techniques
- Results

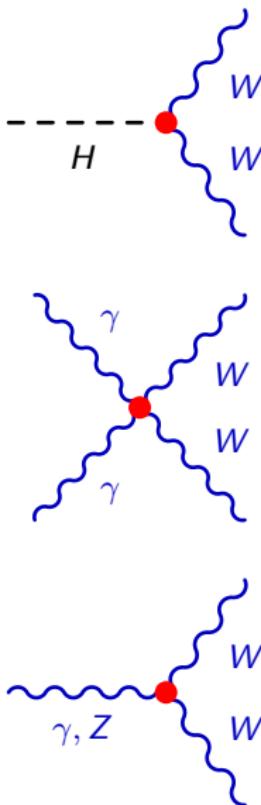
3 Anomalous triple gauge couplings [3]

- Theoretical framework
- Event selection
- Prediction from anomalous couplings
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[1] arXiv:1301.1243 [hep-ex] (accepted by PRD).

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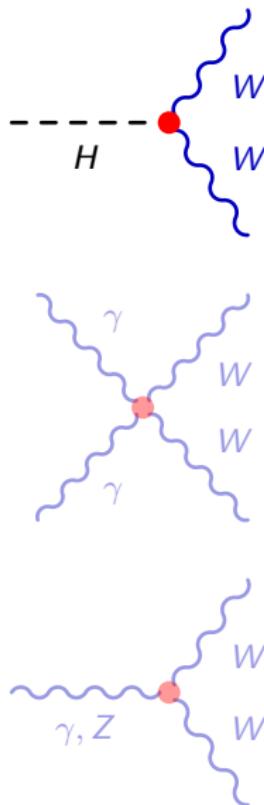
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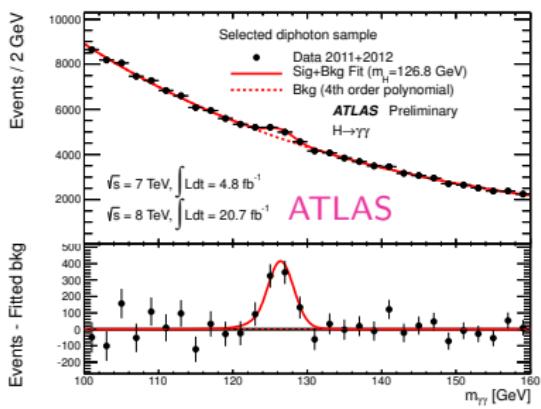
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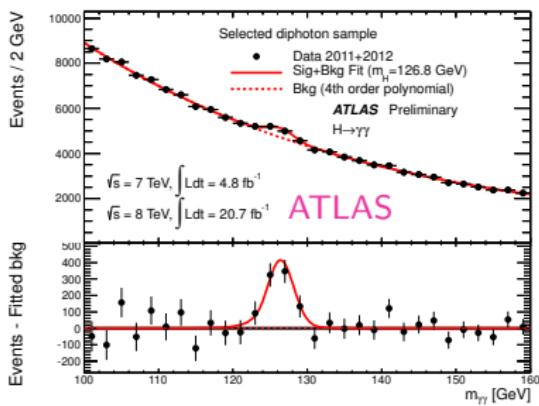
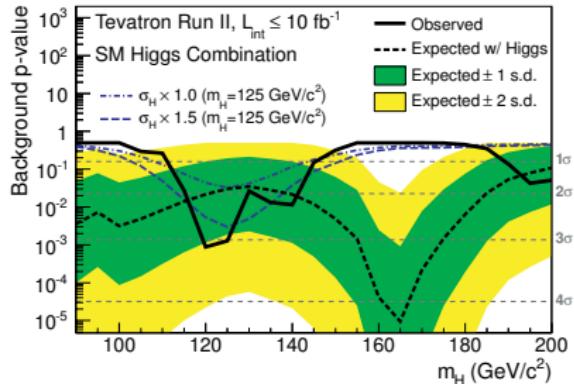
The Higgs boson today

- Mass of fermions and weak vector bosons, regularization of WW scattering, ...
- Discovery at the LHC.



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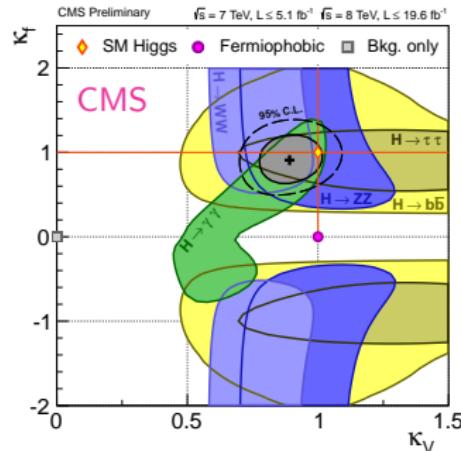
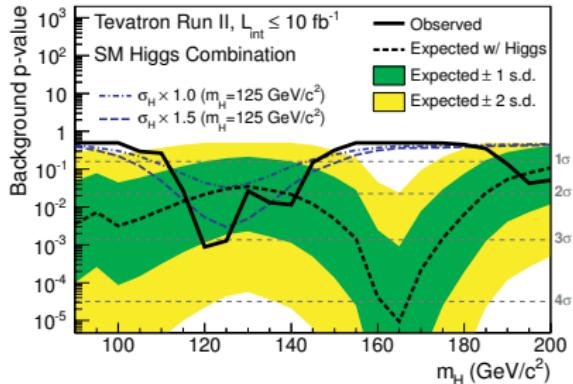
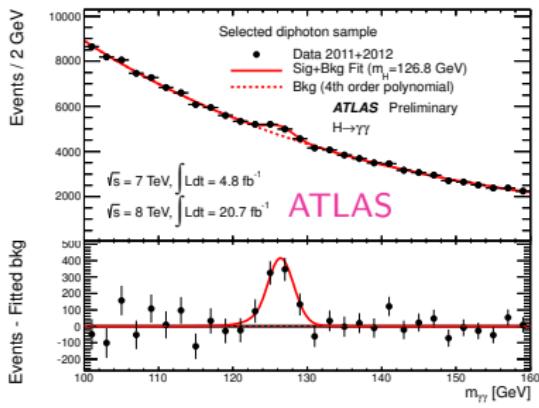
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- Discovery at the LHC.
- 3σ evidence at the Tevatron.



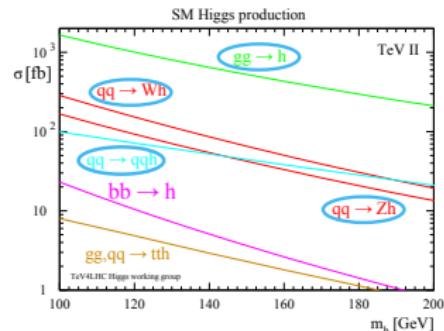
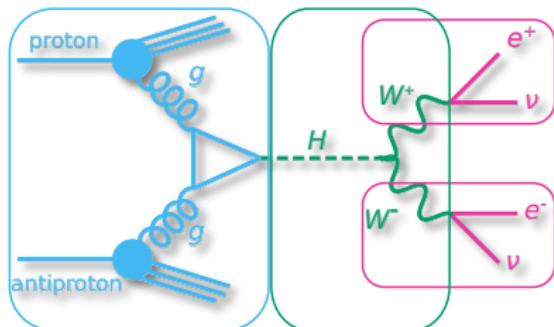


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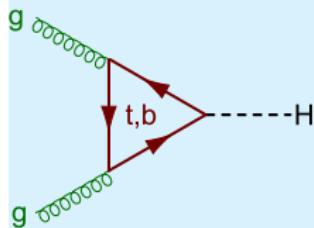
- Mass of fermions and weak vector bosons, regularization of WW scattering, ...
- Discovery at the LHC.
- 3σ evidence at the Tevatron.
- Mass and couplings compatible with SM predictions.



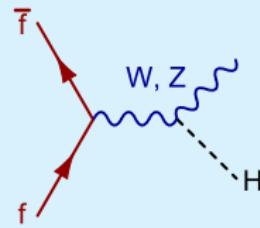
Higgs boson production



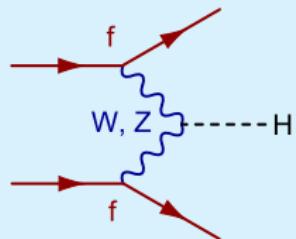
Production modes



gluon-gluon fusion
(a.k.a. ggH)



associated production
(a.k.a Higgsstrahlung, VH)



vector boson fusion
(a.k.a. VBF, qqH)

Physics backgrounds

They all contain two “true” leptons. These backgrounds are estimated from simulation.

$Z/\gamma^* + \text{jets}$ (Drell-Yan)

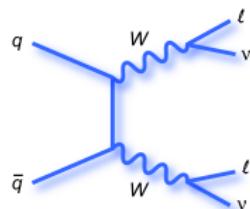
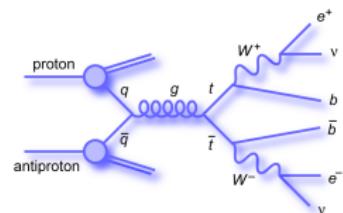
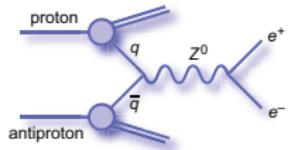
- Huge production cross section ($p\bar{p}$ collider).
- Back to back leptons, no true \cancel{E}_T .

$t\bar{t}$

- Leptons coming from a W boson pair, like for the signal.
- Presence of an additional pair of b -jets.

Diboson (WW , WZ , ZZ)

- Exact same final state as the signal.
- However the signal is a spin-0 resonance.



Instrumental backgrounds

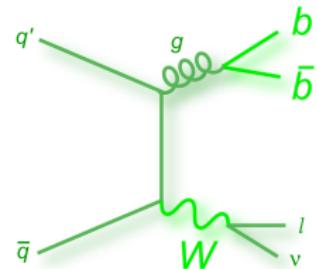
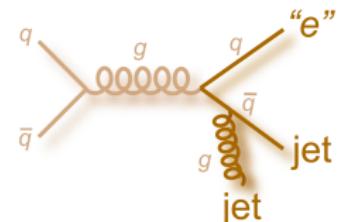
These backgrounds are due to jets or photons being identified as leptons.

Multijet

- No true \cancel{E}_T (no neutrino) in the final state.
- Two low quality leptons.
- Estimated from data.

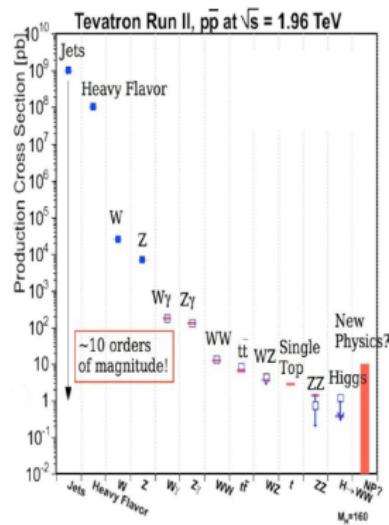
$W+jets$

- Similar topology as the signal (true \cancel{E}_T).
- One of the two leptons has low quality.
- Corrected using data.



General strategy

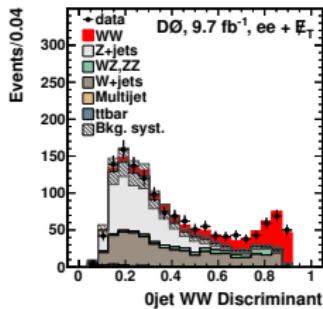
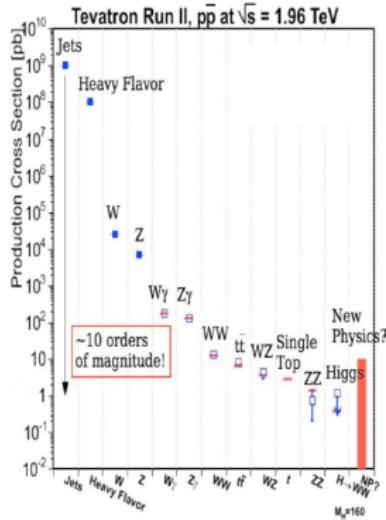
- Very low S/B ratio: maximize acceptance.





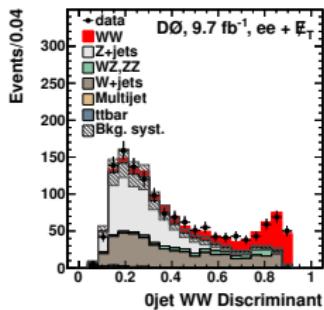
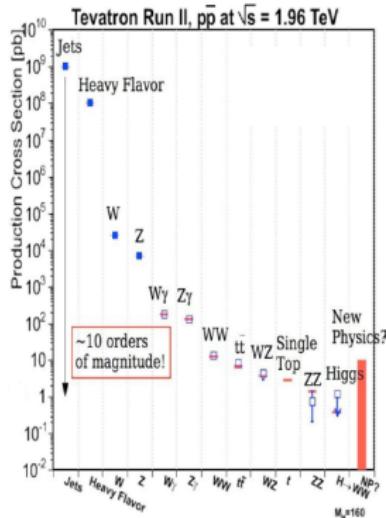
General strategy

- Very low S/B ratio: maximize acceptance.
- Use multivariate analysis (MVA) techniques (e.g. BDTs: Boosted Decision Trees).
 - Combine several variables into one discriminant.
 - Train dedicated discriminants for specific backgrounds (Z/γ^* , WW).



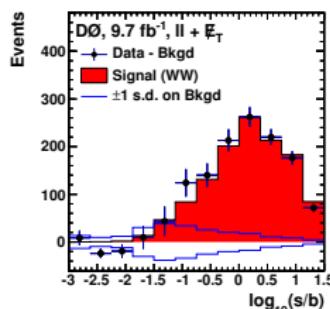
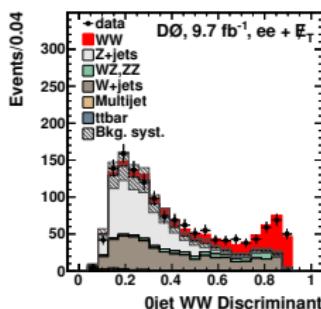
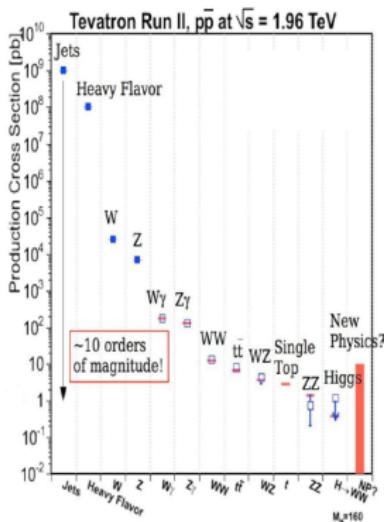
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- Split the analysis into sub-categories.
- Validate analysis technique with a diboson cross-section measurement.



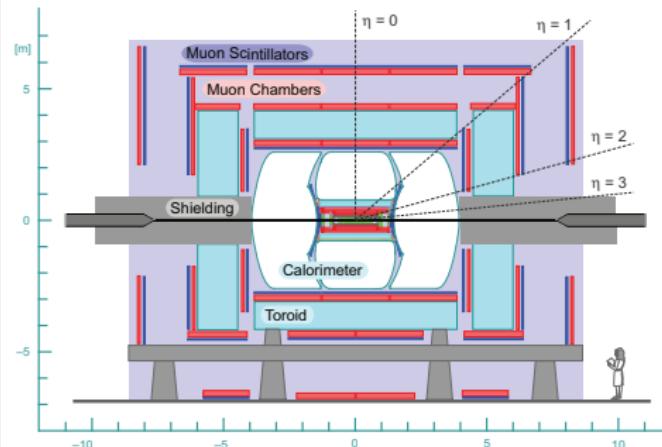
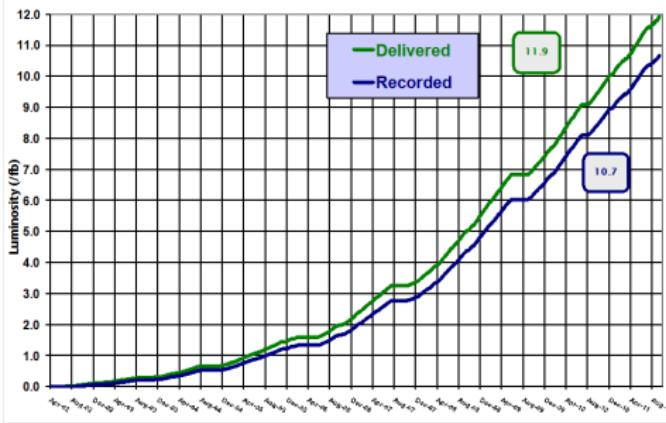


The DØ detector at the Tevatron



Run II Integrated Luminosity

19 April 2002 - 30 September 2011





Corrections to the MC samples

Reweighting

Simulated samples need to be reweighted to take into account various effects:
generator effects because we use LO generators (PYTHIA, ALPGEN): W , Z and Higgs bosons p_T , etc.

- Corrections derived from higher-order generators or from data.

instrumental effects because of imperfect simulation of the detector: E_T modeling, lepton quality, etc.

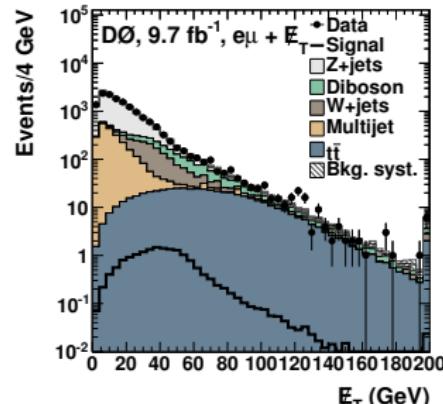
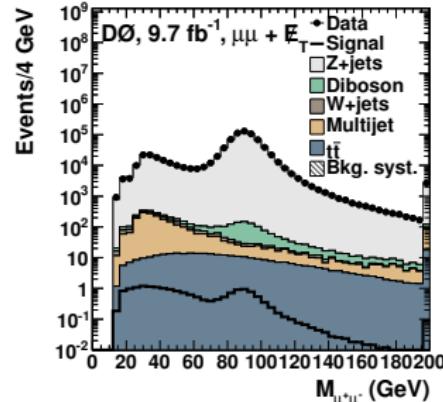


Preselection

Preselection

- Two opposite-sign leptons with $p_T^{1(2)} > 15(10)$ GeV.
 - Electrons: $|\eta_D| < 1.1$ or $1.5 < |\eta_D| < 2.5$.
 - Muons: $|\eta_D| < 2.0$.
- $ee, \mu\mu$: $M_{\ell\ell} > 15$ GeV.
- $e\mu$: $p_T^e > 15$ GeV, $p_T^\mu > 10$ GeV.

- Data — Signal ($M_H = 125$ GeV)
- Z+jets
- W+jets
- tt
- Diboson
- Multijet
- Syst



Classifying events

BDTs in the analysis

Three types of BDTs are used:

- Drell-Yan BDT signal vs. Z/γ^* .
- WW BDT WW vs. other bkg.
- Final discriminant signal vs. all.

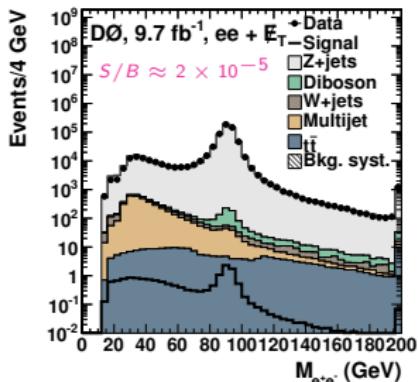
Events are also divided into categories, depending on jet multiplicity and “ WW -likeness” (depending on the WW BDT output or lepton quality).

Event categories

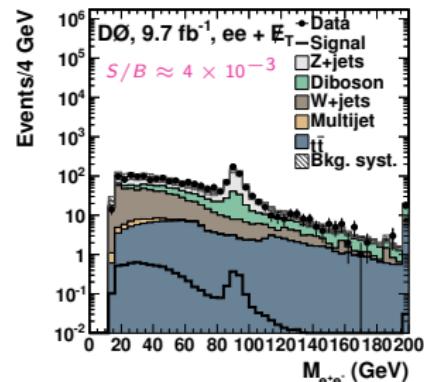
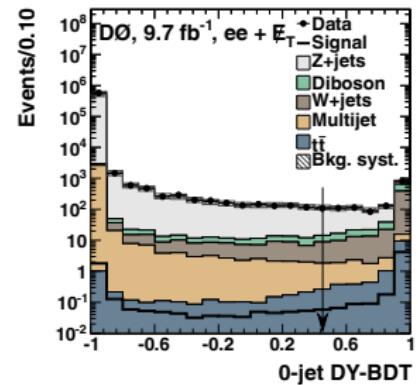
0 jet		1 jet		≥ 2 jets
WW-depleted	WW-enriched	WW-depleted	WW-enriched	

Z/γ^* rejection

- $ee, \mu\mu$: use a BDT to reject the Z/γ^* (Drell-Yan) background. Input variables:
 - Event kinematics and topology (M_{ee} , $\Delta\phi(ee)$, ...).
 - E_T -related ($E_T, \Delta\phi(E_T, e)$, ...).
- $e\mu$: cut on M_T^{\min} and M_{T2} .
 - $M_T(\ell, E_T) = \sqrt{2p_T^\ell E_T [1 - \cos \Delta\phi(\ell, E_T)]}$
- 50 – 75% efficiency on signal, rejects 87 – 99.7% of background.

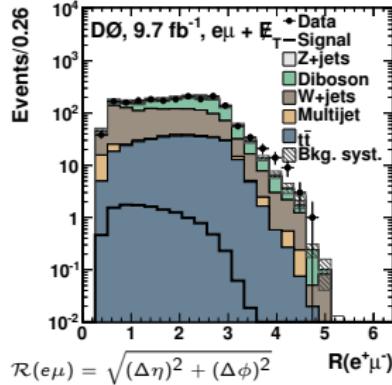
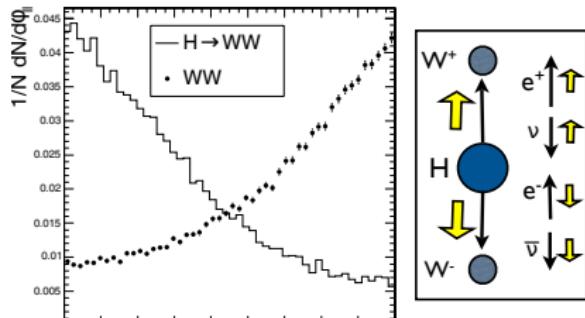
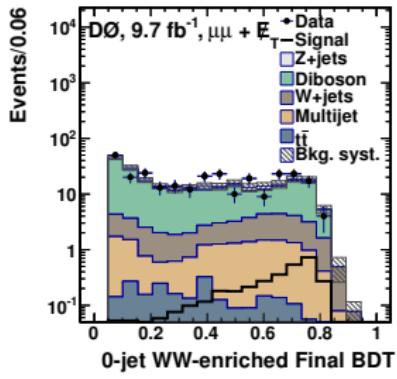


after cutting on
the DY-BDT:
→

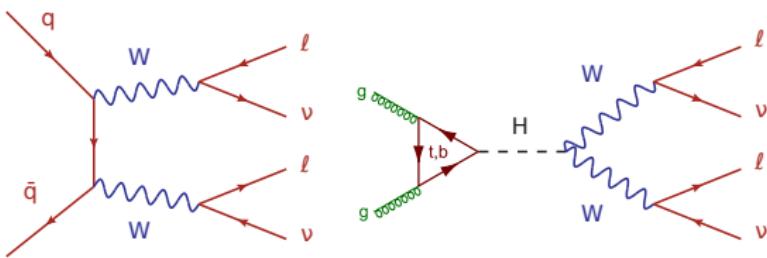


Final discriminant

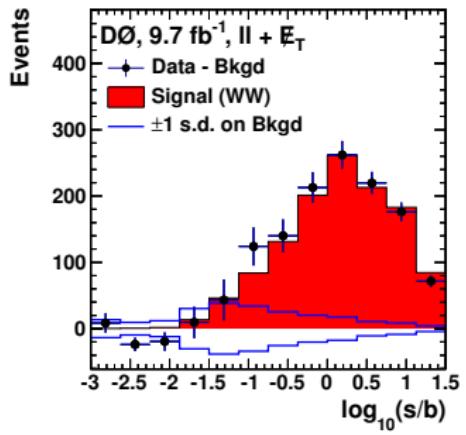
- We use a final BDT to discriminate the signal against the remaining backgrounds.
- Additional information:
 - lepton quality (against $W+jets$),
 - b -tagging information (against $t\bar{t}$),
 - angular variables (against diboson: the Higgs is a spin-0 resonance).



Non-resonant WW cross section measurement



- A cross section measurement of the main irreducible background is a **good cross check for our analyses techniques**.
- Non-resonant WW production is treated as a signal in the training of the MVA.
- We obtain a cross section of
 $\sigma_{p\bar{p} \rightarrow WW} = 11.4 \pm 0.4 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb.}$
- Theoretical cross section:
 $\sigma_{p\bar{p} \rightarrow WW} = 11.34 \pm 0.7 \text{ pb}^a.$



^aCampbell and Ellis, Phys. Rev. D **60**, 113006 (1999).



The Poisson χ^2

- χ^2 function for hypothesis H_0 or H_1 (resp. background only and signal + background).
- Systematic uncertainties (signal and background normalizations (cross sections), modeling effects, etc.) are taken into account as nuisance parameters in the fit (R_k).

$$\chi^2(H) = -2 \ln P(\text{data}|H, R_k) = 2 \sum_{i=1}^{N_{\text{bins}}} (p(H)'_i - d_i) - d_i \ln \left(\frac{p(H)'_i}{d_i} \right) + \sum_{k=1}^{N_{\text{syst}}} R_k^2$$

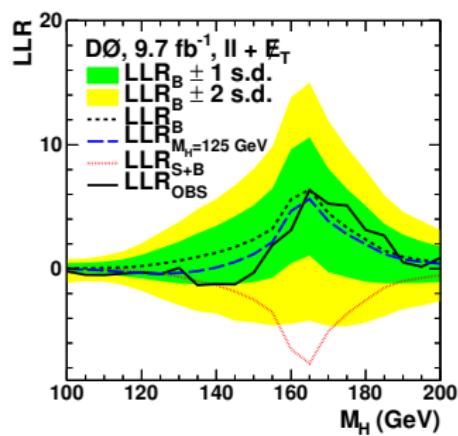
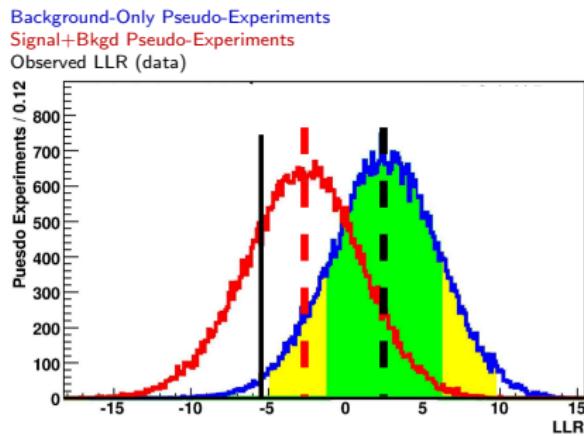
where $R_k \equiv$ deviation from central value of syst. uncertainty k in s.d.

Log-likelihood distributions

- The log-likelihood ratio helps to gauge the relative agreement of the data with the H_0 and H_1 models:

$$\text{LLR} = -2 \ln \left(\frac{P(\text{data}|H_1)}{P(\text{data}|H_0)} \right)$$

- Distributions are populated with pseudo-experiments to get an estimate of significance (include fluctuations from statistics and systematic uncertainties).

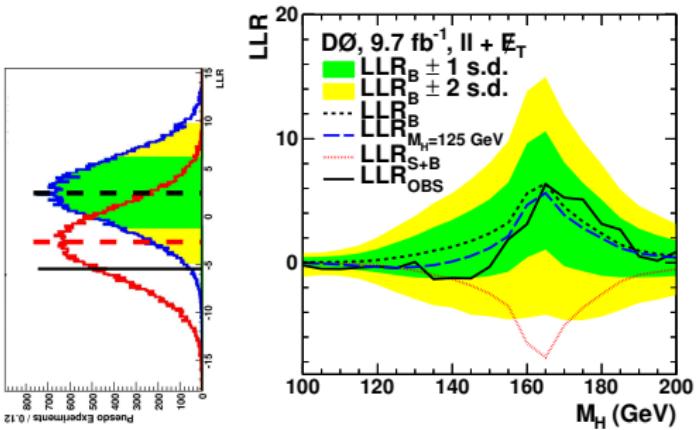


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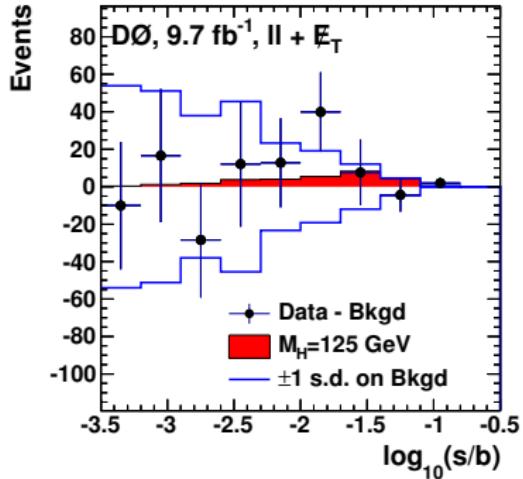
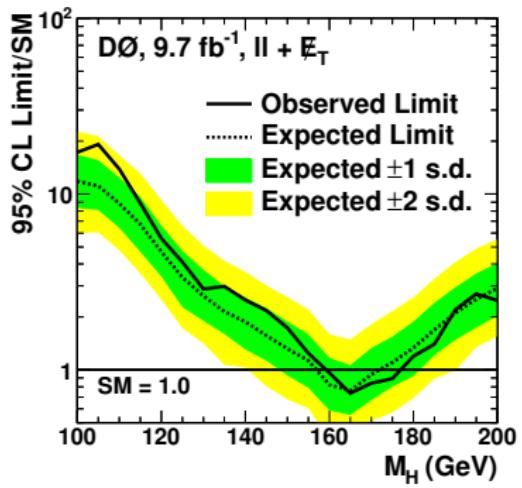
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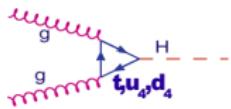
Upper limits on SM Higgs boson cross section



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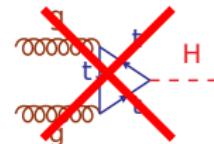
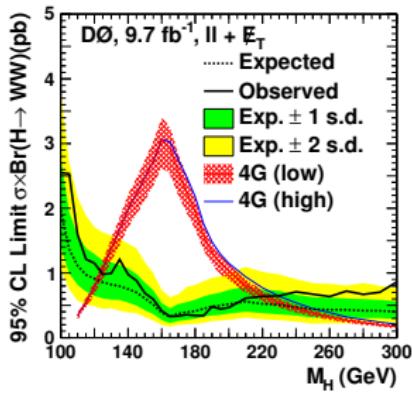
- No substantial excess of events is observed.
- Observed (expected) exclusion: $159 < M_H < 176$ GeV
 $(156 < M_H < 172$ GeV).

Beyond the Standard Model



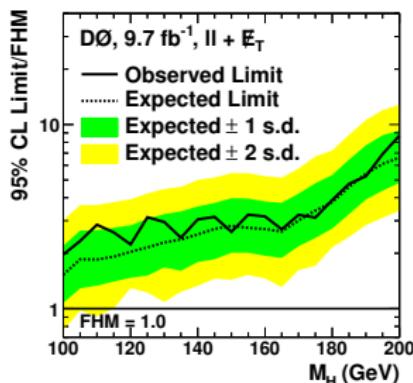
Fourth generation of fermions

Enhancement of $\sigma(gg \rightarrow H)$ by a factor 7 to 9.



Fermiophobic Higgs

Unchanged couplings to bosons compared to the SM, zero couplings to fermions.



Summary of the search for the Higgs boson in the WW channel

- Measurement of the non-resonant WW production:
 $\sigma_{p\bar{p} \rightarrow WW} = 11.4 \pm 0.4 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb.}$
- SM Higgs boson search:
 - Exclude the range $159 < M_H < 176 \text{ GeV}$.
 - Small excess compatible with a Higgs boson of $M_H = 125 \text{ GeV}$.
- BSM scenarios:
 - Fourth generation: exclude $125 < M_H < 218 \text{ GeV}$.
 - Fermiophobic Higgs: exclude 3.1 times the fermiophobic Higgs boson production rate at $M_H = 125 \text{ GeV}$.

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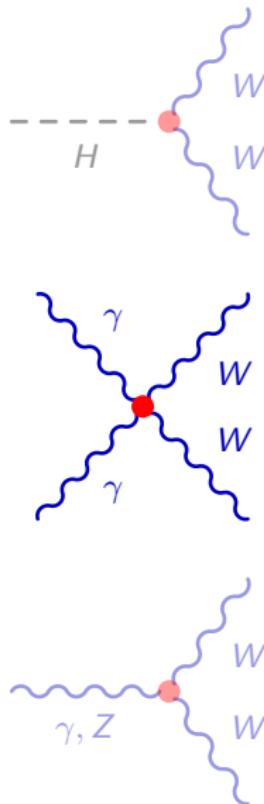
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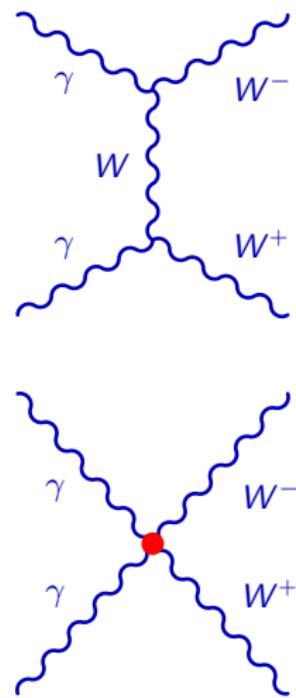
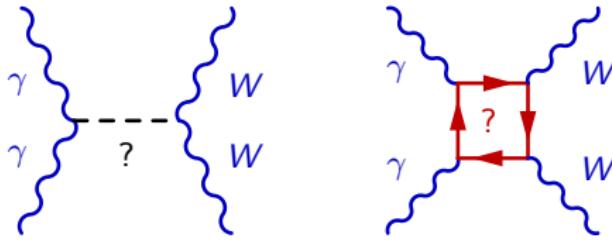
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Two-photon interaction at the Tevatron

- Study of the QED process $p\bar{p} \rightarrow p\bar{p}WW$
- Very small cross section in the Standard Model ($\sigma_{p\bar{p} \rightarrow p\bar{p}WW} = 3 \text{ fb}$ at $\sqrt{s} = 1.96 \text{ TeV}$).
- Sensitivity to beyond standard model effects, especially anomalous couplings (which can arise from e.g. models with extra dimensions).

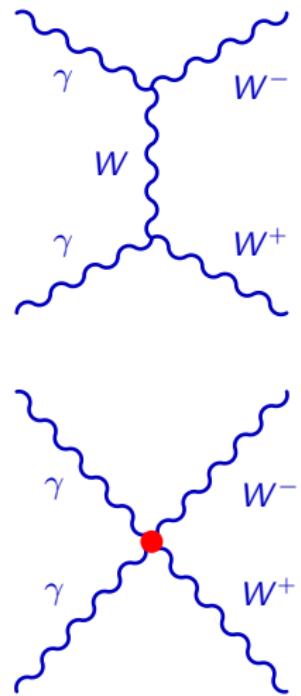




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- Sensitivity to beyond standard model effects, especially anomalous couplings (which can arise from e.g. models with extra dimensions).
- In this analysis we only study anomalous quartic gauge couplings (AQGCs), and not triple gauge couplings (TGCs).

Analysis based on the search for $H \rightarrow WW \rightarrow e\nu e\nu$.





Lagrangians

Effective lagrangian for AQGCs $WW\gamma\gamma$ with C and P invariance (dim-6):

$$\mathcal{L}_6^0 = \frac{-e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_\alpha^-$$

$$\mathcal{L}_6^C = \frac{-e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_\beta^- + W^{-\alpha} W_\beta^+)$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor and W_α^\pm is the W^\pm boson field.

Both anomalous parameters a_0^W and a_C^W are 0 in the SM.

Unitarity

If nothing is done, unitarity is violated at high energies. Introduce a form-factor:
 $a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W_{\gamma\gamma}^2/\Lambda^2)^2}$ where $\Lambda \sim$ scale of new physics (typical values from literature^a: $\Lambda = 0.5$ TeV or 1 TeV).

^ae.g. Eboli *et al.*, Phys. Rev. D **63**, 075008 (2001)



Previous results

Current best published limits: OPAL

Without form-factor:

$$\begin{aligned} -0.020 &< a_0^W/\Lambda^2 < 0.020 \text{ GeV}^{-2} \\ -0.052 &< a_C^W/\Lambda^2 < 0.037 \text{ GeV}^{-2} \end{aligned}$$

Phys. Rev. D **70**, 032005 (2004) [arXiv:hep-ex/0402021].

Recent CMS limits

Without form-factor:

$$\begin{aligned} -2.8 \times 10^{-6} &< a_0^W/\Lambda^2 < 2.8 \times 10^{-6} \text{ GeV}^{-2} \\ -1.02 \times 10^{-5} &< a_C^W/\Lambda^2 < 1.02 \times 10^{-5} \text{ GeV}^{-2} \end{aligned}$$

With a form-factor with $\Lambda = 500 \text{ GeV}$:

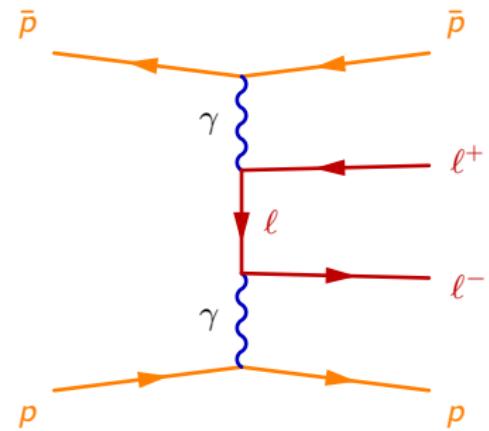
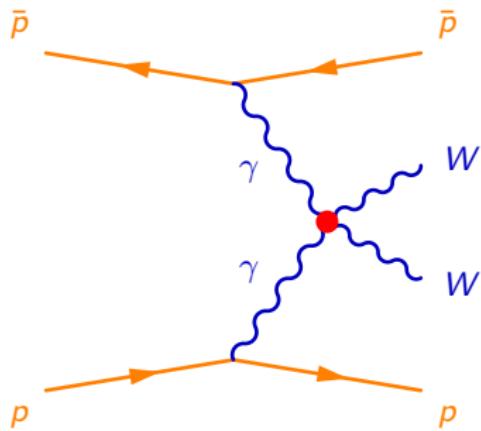
$$\begin{aligned} -0.00017 &< a_0^W/\Lambda^2 < 0.00017 \text{ GeV}^{-2} \\ -0.0006 &< a_C^W/\Lambda^2 < 0.0006 \text{ GeV}^{-2} \end{aligned}$$

arXiv:1305.5596 [hep-ex] (CMS-PAS-FSQ-12-010).

Signal and background modeling

Photon exchange and double pomeron exchange processes

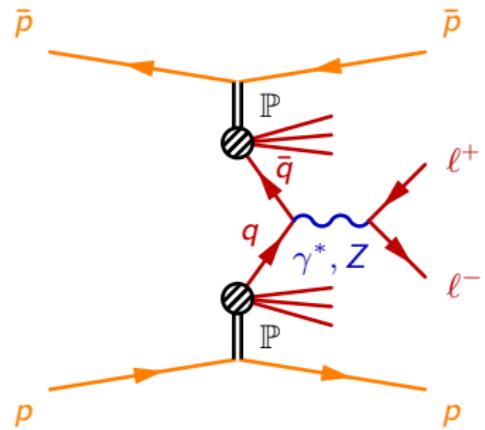
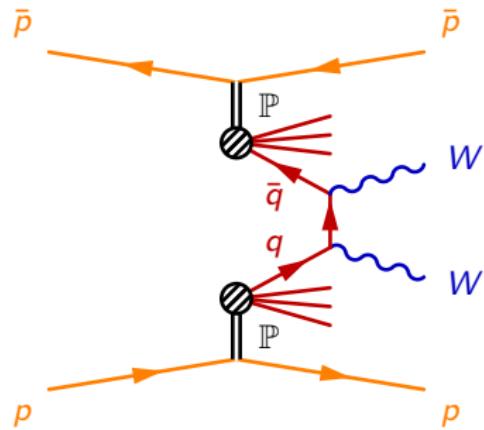
- Signal: $p\bar{p} \rightarrow p\bar{p}WW$ through photon exchange, with AQGCs.
- Diffractive backgrounds: WW and $\ell\ell$ production through photon exchange or double pomeron exchange (DPE).
- Processes modeled using Forward Physics Monte-Carlo (FPMC).



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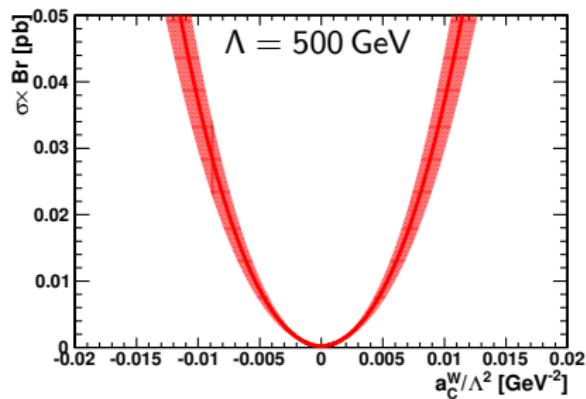
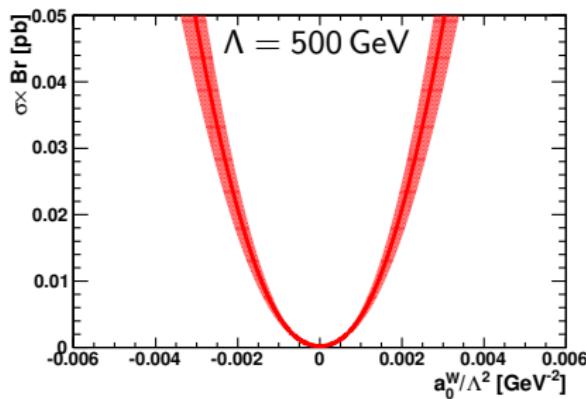
Non-diffractive backgrounds

- Physics backgrounds: $Z/\gamma^* + \text{jets}$, $t\bar{t}$, diboson (WW , WZ , ZZ).
- Instrumental backgrounds: $W + \text{jets}$, multijet.
- Modeled using PYTHIA or ALPGEN + PYTHIA.
 - Multijet background fully determined from data.

Signal cross section

Cross sections

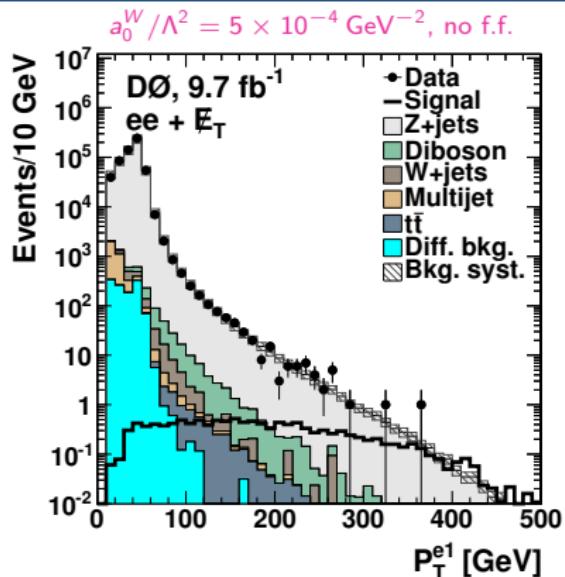
- In the SM: $\sigma_{p\bar{p} \rightarrow p\bar{p}WW} = 3 \text{ fb}$ ($\rightarrow 0.1$ event after event selection).
- 10 – 100 times enhancement with anomalous couplings.



Preselection

Preselection based on the $H \rightarrow WW$ analysis

- Restrict to the ee final state.
- Veto events with one or more jets with $p_T > 20$ GeV.
- Signal: $p\bar{p} \rightarrow p\bar{p}WW$ with AQGCs.

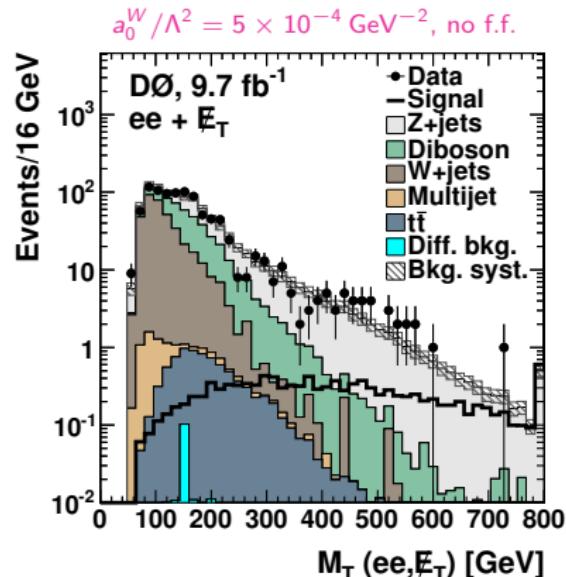
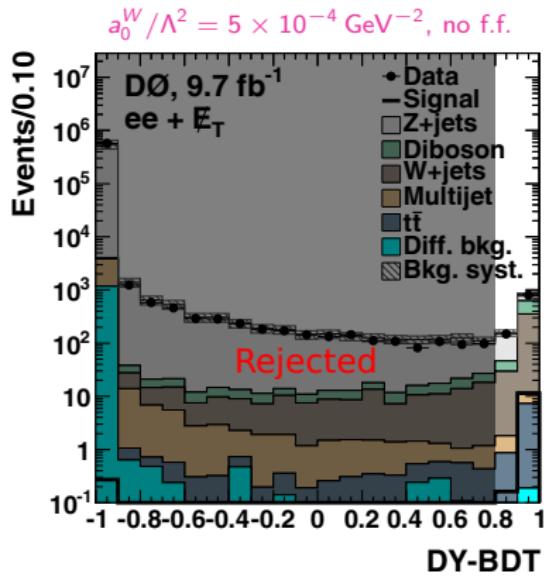


Expectation from AQGCs

- Boosted WW pair.
- Similar effects from a_0^W/Λ^2 and a_C^W/Λ^2 .

$Z/\gamma^* + \text{jets}$ rejection

Dominant $Z/\gamma^* + \text{jets}$ background rejected thanks to a cut on a Boosted Decision Tree (BDT).

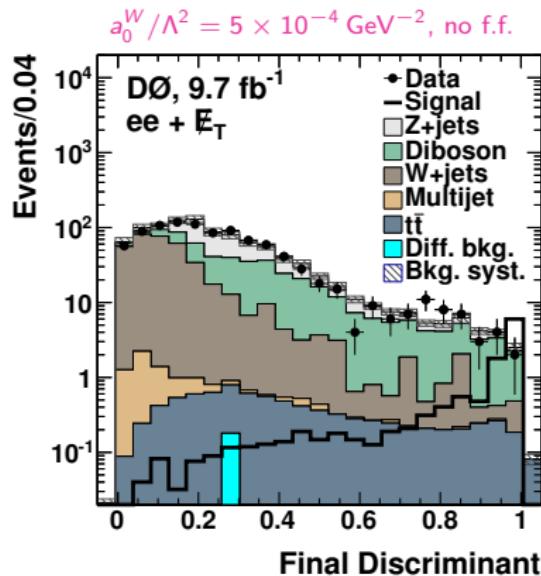




Event yields

	Preselection	Final selection
Data	572700	946
Total background	576576 ± 11532	983 ± 108
Signal ($a_0^W/\Lambda^2 = 5 \times 10^{-4} \text{ GeV}^{-2}$, no f.f.)	12.2	11.6
$Z/\gamma^* \rightarrow ee$	566800	291
$Z/\gamma^* \rightarrow \tau\tau$	4726	22
$t\bar{t}$	15	8
$W+\text{jets}$	623	370
Diboson	517	287
Multijet	2716	5.4
Diffractive bkg. (γ exch. and DPE)	1180	0.2

Final discriminant



A second BDT is used as final discriminant.

- The same BDT is used for both a_0^W / Λ^2 and a_C^W / Λ^2 .
- No excess of events is observed: proceed to set limits.



Single-parameter limits

Table: Expected and observed 95% C.L upper limits on $|a_0^W/\Lambda^2|$, assuming a_C^W is zero and for different assumptions about the form factor.

Cutoff	Expected upper limit [GeV^{-2}]	Observed upper limit [GeV^{-2}]
No form factor	0.00043	0.00043
$\Lambda = 1 \text{ TeV}$	0.00092	0.00089
$\Lambda = 0.5 \text{ TeV}$	0.0025	0.0025

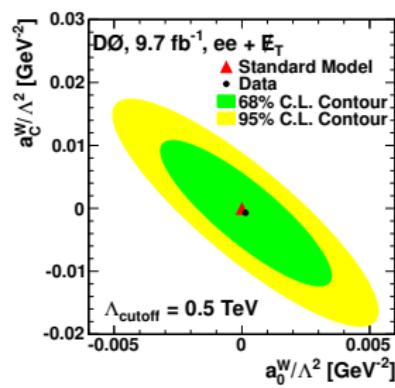
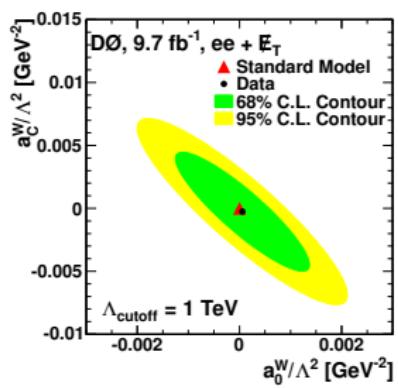
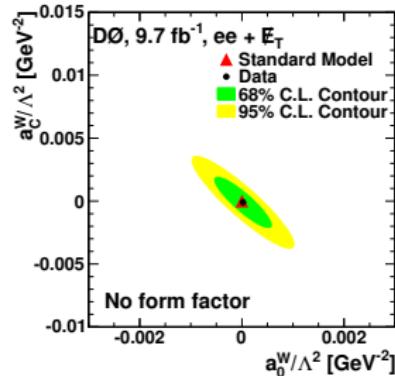
Table: Expected and observed 95% C.L upper limits on $|a_C^W/\Lambda^2|$, assuming a_0^W is zero and for different assumptions about the form factor.

Cutoff	Expected upper limit [GeV^{-2}]	Observed upper limit [GeV^{-2}]
No form factor	0.0016	0.0015
$\Lambda = 1 \text{ TeV}$	0.0033	0.0033
$\Lambda = 0.5 \text{ TeV}$	0.0090	0.0092

Two-parameter limits

Procedure

Based on the upper limit on the signal cross section obtained in the single parameter limits.



Outline

1 Search for the Higgs boson in the WW channel [1]

- Analysis overview
- Hunting down the Higgs boson
- Results

2 Anomalous quartic gauge couplings [2]

- Theoretical framework
- Data and MC samples
- Analysis techniques
- Results

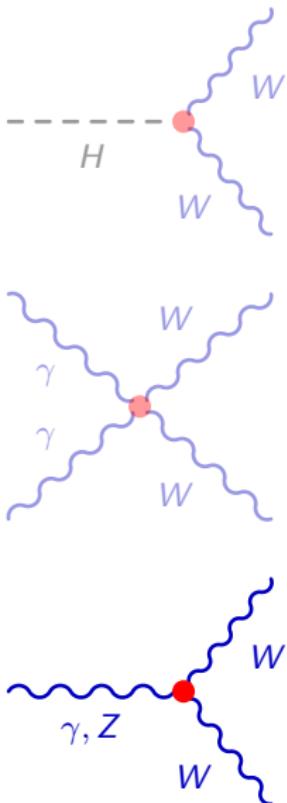
3 Anomalous triple gauge couplings [3]

- Theoretical framework
- Event selection
- Prediction from anomalous couplings
- Results

[1] arXiv:1301.1243 [hep-ex] (accepted by PRD).

[2] arXiv:1305.1258 [hep-ex] (submitted to PRD – RC).

[3] Phys. Lett. B **718**, 451 (2012) [arXiv:1208.5458 [hep-ex]].



Anomalous triple gauge couplings

Lagrangian (assuming C and P conservation and EM gauge invariance)

$$\frac{\mathcal{L}_{VWW}}{g_{VWW}} = ig_1^\gamma (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda}$$

with $V = Z$ or γ , $g_{\gamma WW} = -e$ and $g_{ZWW} = -e \cot \theta_W$.

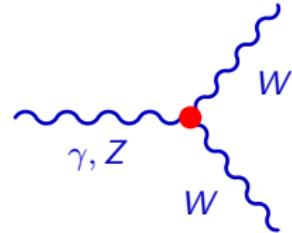
SM: $\lambda_\gamma = \lambda_Z = 0$, $g_1^\gamma = g_1^Z = \kappa_\gamma = \kappa_Z = 1$.

Assumptions

- Two scenarios:
 - LEP parametrization ($SU(2) \times U(1)$ gauge invariance):

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2 \theta_W, \quad \lambda_Z = \lambda_\gamma = \lambda$$
 - Equal couplings:

$$\Delta\kappa_Z = \Delta\kappa_\gamma = \Delta\kappa, \quad \lambda_Z = \lambda_\gamma = \lambda, \quad \Delta g_1^\gamma = \Delta g_1^Z = 0$$
- Unitarity: cutoff $\Lambda = 2 \text{ TeV}$, scale of new physics.



Analyses entering the combination

Combination of several final states

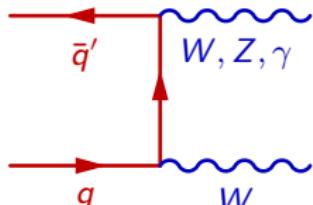
- Search for anomalous WWZ and $WW\gamma$ couplings in the final states:

$WW + WZ$	\rightarrow	$\ell\nu jj$	(4.3 fb^{-1})	Phys. Lett. B 718 , 451 (2012)
WZ	\rightarrow	$\ell\nu\ell\ell$	(8.6 fb^{-1})	Phys. Lett. B 718 , 451 (2012)
$W\gamma$	\rightarrow	$\ell\nu\gamma$	(0.70 fb^{-1})	Phys. Rev. Lett. 100 , 241805 (2008)
$W\gamma$	\rightarrow	$\ell\nu\gamma$	(4.2 fb^{-1})	Phys. Rev. Lett. 107 , 241803 (2011)
WW	\rightarrow	$\ell\nu\ell\nu$	(1 fb^{-1})	Phys. Rev. Lett. 103 , 191801 (2009)
$WW + WZ$	\rightarrow	$\ell\nu jj$	(1.1 fb^{-1})	Phys. Rev. D 80 , 053012 (2009)

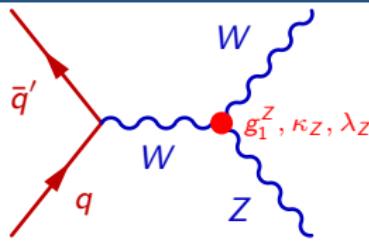
Includes the only searches for ATGCs in the $\ell\nu jj$ channel!



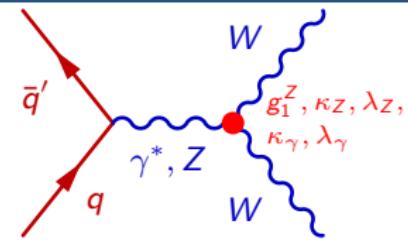
Sensitivity to anomalous triple gauge couplings



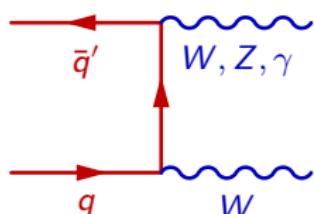
t-channel dominates total cross section



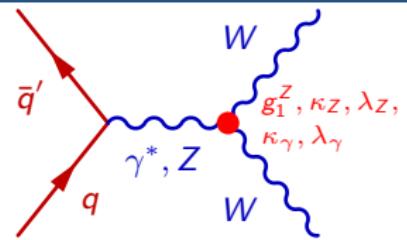
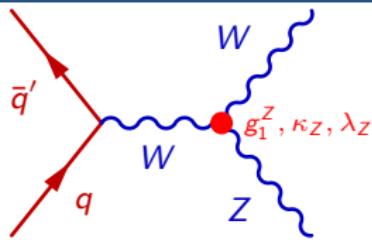
s-channel is sensitive to ATGCs



Sensitivity to anomalous triple gauge couplings



t-channel dominates total cross section



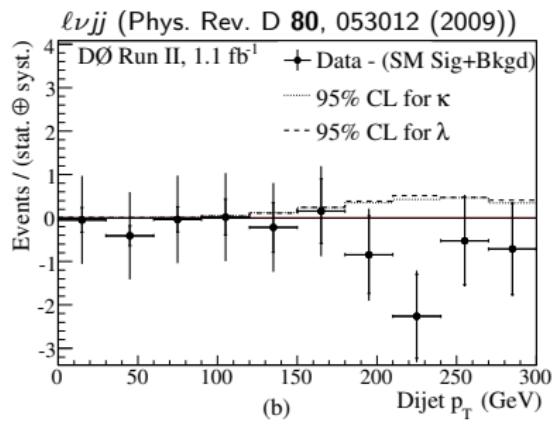
s-channel is sensitive to ATGCs

Variable sensitive to ATGCs

Look for deviation in some kinematic distribution:

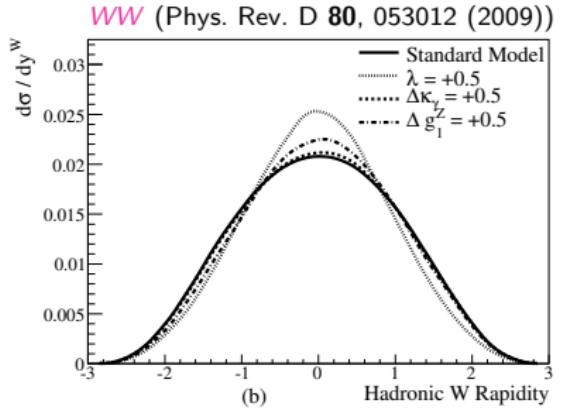
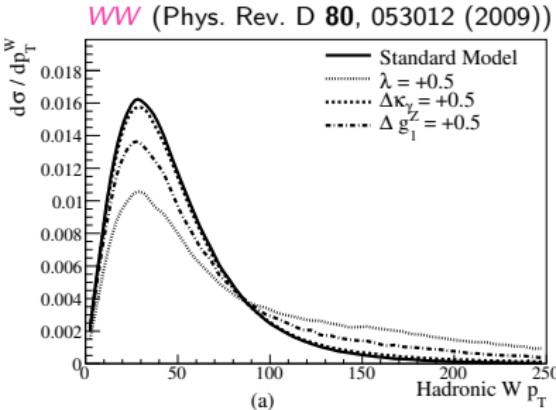
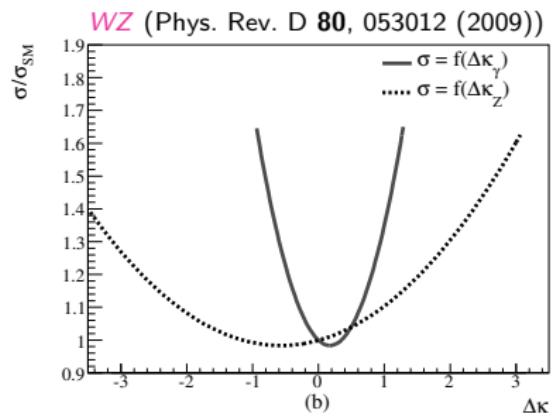
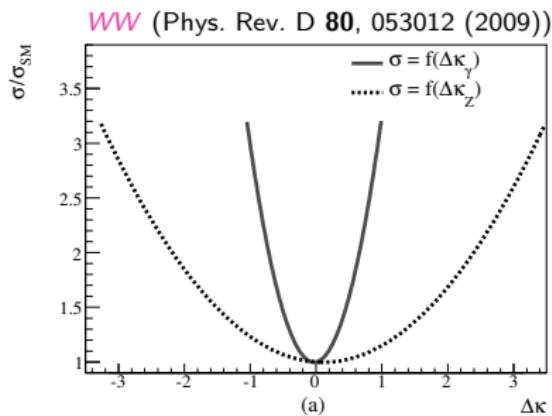
$$\begin{aligned} WW + WZ &\rightarrow \ell\nu jj \\ WZ &\rightarrow \ell\bar{\nu}\ell\bar{\nu} \\ W\gamma &\rightarrow \ell\nu\gamma \\ WW &\rightarrow \ell\nu\ell\nu \end{aligned}$$

$$\begin{aligned} \text{dijet } p_T &\\ \text{dilepton } p_T &\\ \text{photon } E_T &\\ \text{leptons } p_T & \end{aligned}$$





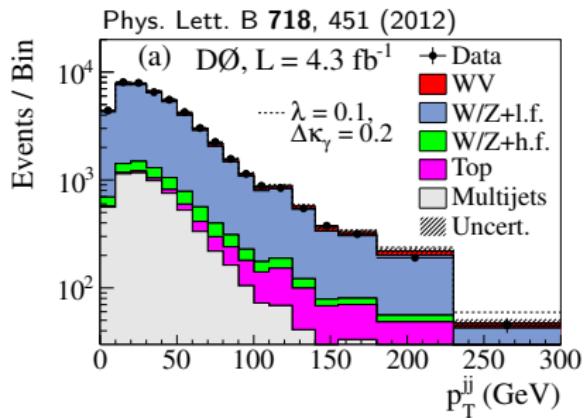
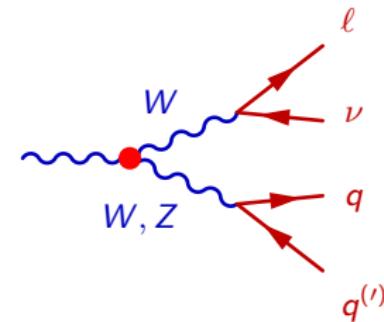
Signal cross section (LEP parametrization)



$WW + WZ \rightarrow \ell\nu jj$

Event selection

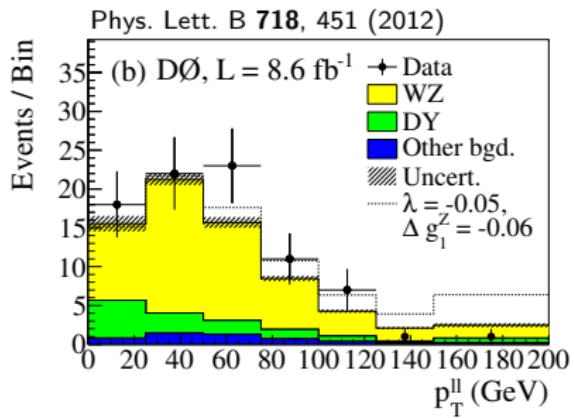
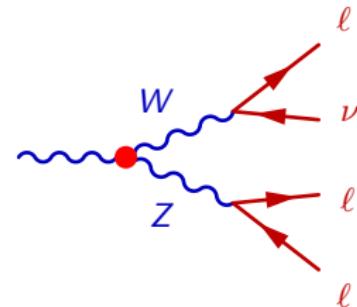
- A single electron or muon
 - Electron: $p_T > 15 \text{ GeV}$, $|\eta| < 1.1$
 - Muon: $p_T > 20 \text{ GeV}$, $|\eta| < 2.0$
- $\cancel{E}_T > 20 \text{ GeV}$
- Two or three jets ($p_T > 20 \text{ GeV}$, $|\eta| < 2.5$)
- $55 < M_{jj} < 110 \text{ GeV}$
- W transverse mass cut:
 $M_T^{\ell\nu} > 40 \text{ GeV} - 0.5 \cancel{E}_T$

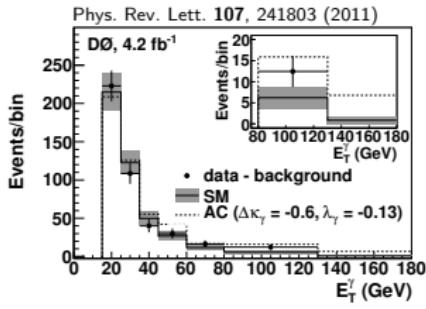
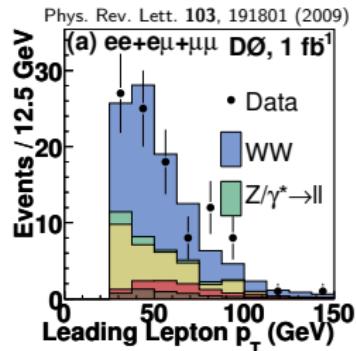
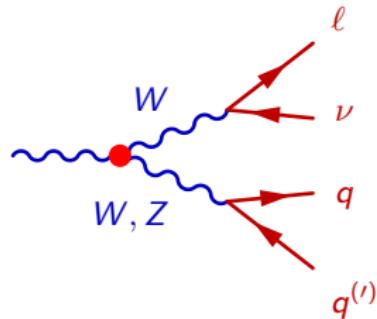
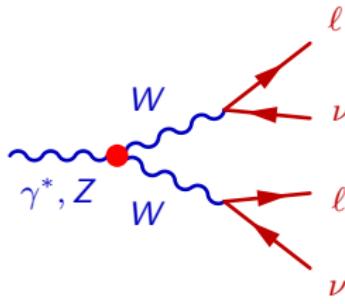
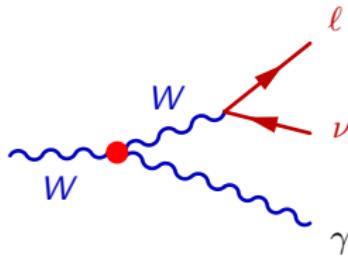
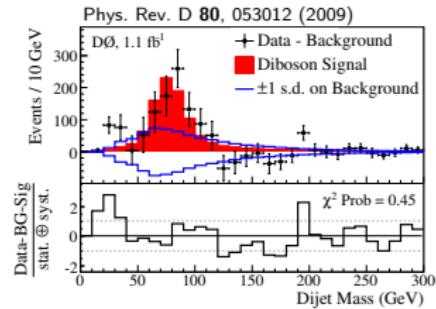


$WZ \rightarrow \ell\nu\ell\ell$

Event selection

- At least two oppositely charged electrons or muons
 - Electrons: $p_T^1 > 20 \text{ GeV}$,
 $p_T^2 > 15 \text{ GeV}$, $|\eta| < 3.0$
 - Muons: $p_T^1 > 15 \text{ GeV}$,
 $p_T^2 > 10 \text{ GeV}$, $|\eta| < 2.0$
 - $60 < M_{\ell\ell} < 120 \text{ GeV}$
- Additional electron or muon with $p_T > 15 \text{ GeV}$



$W\gamma \rightarrow \ell\nu\gamma, WW \rightarrow \ell\nu\ell\nu, WW + WZ \rightarrow \ell\nu jj$
 $W\gamma \rightarrow \ell\nu\gamma$  $WW \rightarrow \ell\nu\ell\nu$  $WW + WZ \rightarrow \ell\nu jj$ 



Expected signal from anomalous couplings ($\ell\nu jj$, $\ell\nu\ell\ell$)

Two-step procedure

- ➊ NLO prediction of the boson p_T spectrum in the SM.
 - PYTHIA reweighted to MC@NLO (and passed through a detailed GEANT-based simulation of the detector).
 - NLO cross section from MCFM: $\sigma(WW) = 11.7 \pm 0.8 \text{ pb}$, $\sigma(WZ) = 3.5 \pm 0.3 \text{ pb}$.
- ➋ Reweight this distribution to the prediction with ATGCs (from MCFM):

$$R \propto \frac{\sigma}{\sigma_{\text{SM}}}$$

$$\begin{aligned} d\sigma &\propto |\mathcal{M}|^2 dX \\ &\propto |\mathcal{M}|_{\text{SM}}^2 \frac{|\mathcal{M}|^2}{|\mathcal{M}|_{\text{SM}}^2} dX \\ &\propto d\sigma_{\text{SM}} \cdot R(\Delta\kappa, \lambda, \dots) \end{aligned}$$

where X is a variable sensitive to ATGCs: $X = p_T^{jj}, p_T^{\ell\ell}$



Details of the reweighting ($\ell\nu jj$, $\ell\nu ll$)

Quadratic dependence of the differential cross section on ATGCs.

$$\begin{aligned} R &= \frac{|\mathcal{M}|^2}{|\mathcal{M}_{\text{SM}}|^2} \\ &= 1 + A(Y)\Delta\kappa + B(Y)\Delta\kappa^2 + C(Y)\lambda + D(Y)\lambda^2 + E(Y)\Delta\kappa\lambda + \dots \end{aligned}$$

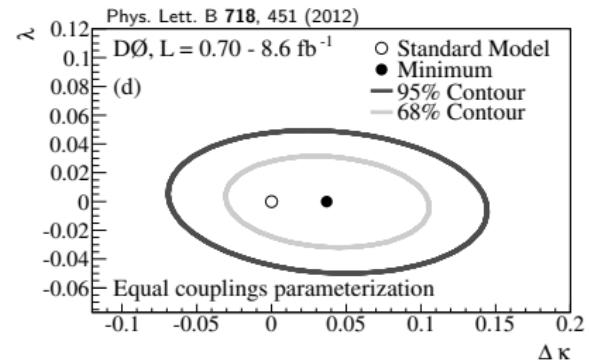
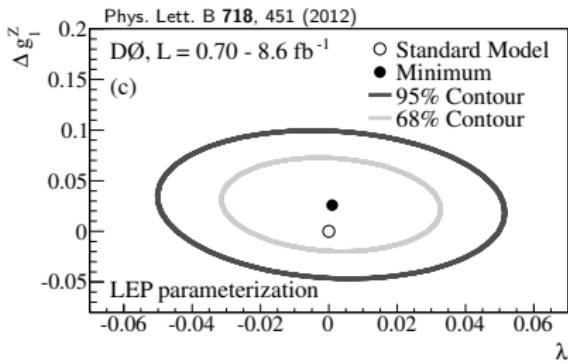
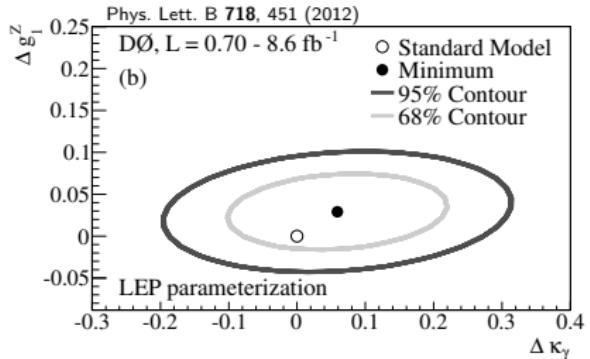
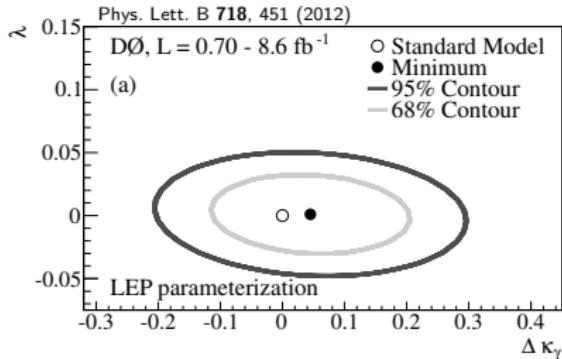
- Two scenarios:
 - Equal couplings: 2 parameters ($\Delta\kappa, \lambda$) → 5 coefficients (A, B, C, D, E)
 - LEP parametrization: 3 parameters ($\Delta\kappa, \lambda, \Delta g_1^Z$) → 9 coefficients
- Parton-level variables Y :
 - $\ell\nu jj$: 6D ($p_T^{q\bar{q}}, p_T^\ell, p_T^\nu$, leading and trailing quark $p_T, M_{q\bar{q}}$)
 - $\ell\nu ll$: 5D (p_T^Z, p_T of leading and trailing lepton from the Z , p_T of the lepton and the neutrino from the W)

Grid of predictions from anomalous couplings

- **Fast**: get the prediction of any set of ATGCs without running the full simulation again.
- **Precise**: reweighted distribution and actual ATGC distribution from MC@NLO agree within 5%.



Two-parameter limits

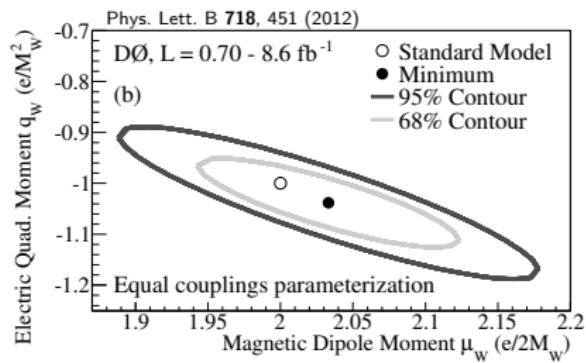
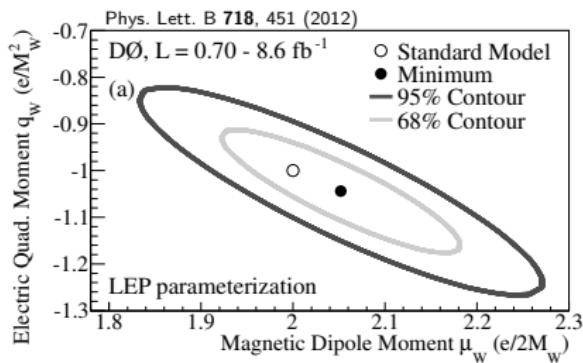




Magnetic dipole and electric quadrupole of the W boson

Definition

$$\mu_W = \frac{e}{2M_W} (1 + \kappa_\gamma + \lambda_\gamma), \quad q_W = -\frac{e}{M_W^2} (\kappa_\gamma - \lambda_\gamma)$$

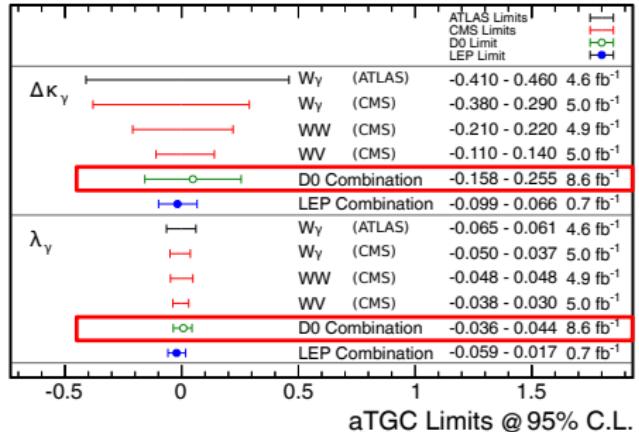


Most stringent limits to date on μ_W and q_W .

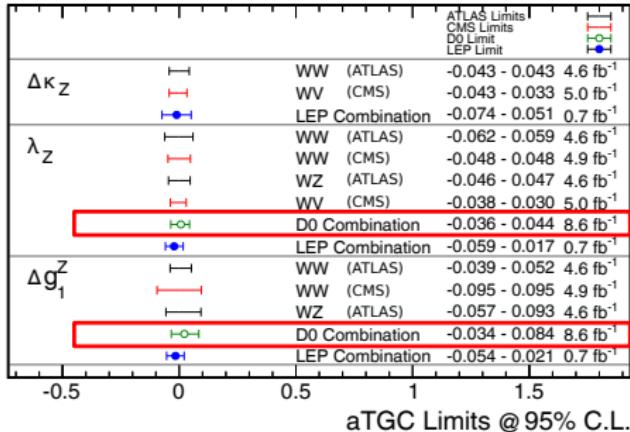


One-parameter limits and comparison with other experiments

Feb 2013



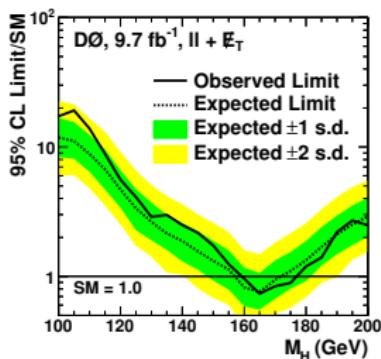
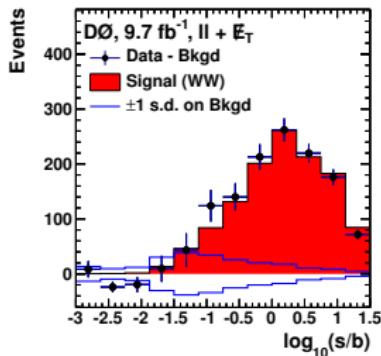
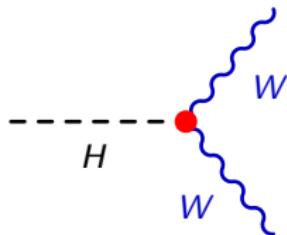
Feb 2013



Summary

WW production as a probe to the electroweak sector

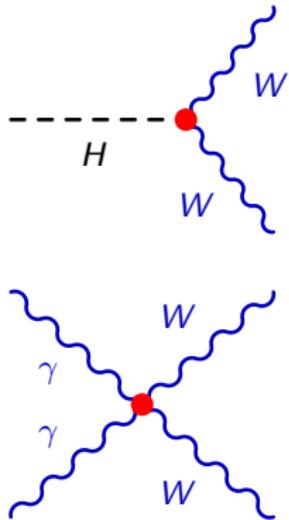
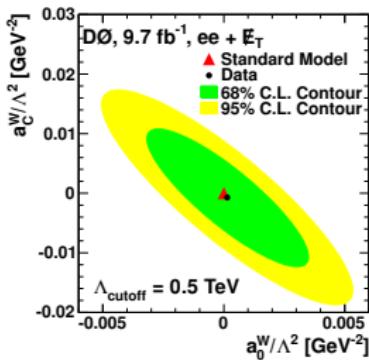
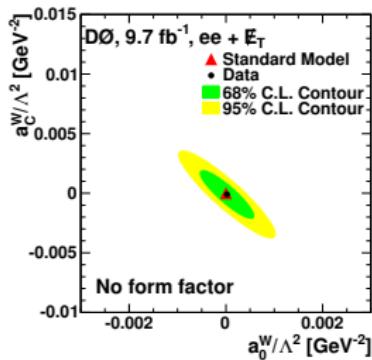
- Higgs boson search in the WW channel:
 - WW cross section measurement.
 - Exclusion range: $159 < M_H < 176 \text{ GeV}$.



Summary

WW production as a probe to the electroweak sector

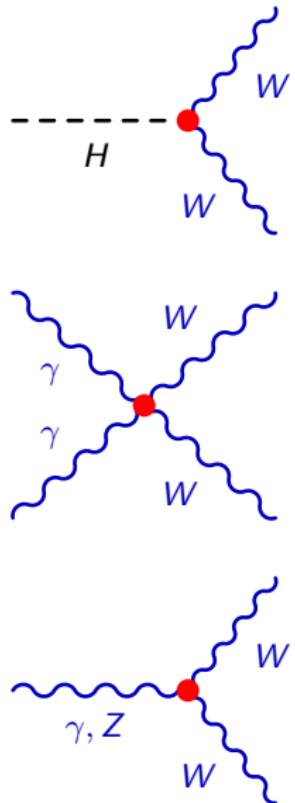
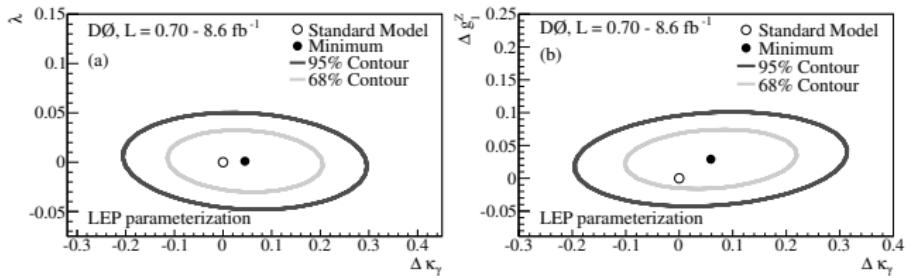
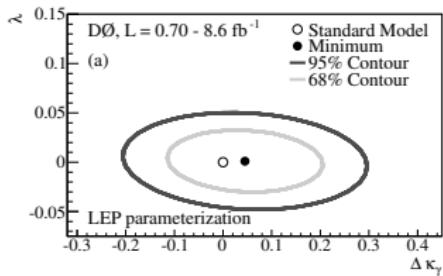
- Higgs boson search in the WW channel:
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- Anomalous quartic gauge boson couplings:
 - First limits from the Tevatron.



Summary

WW production as a probe to the electroweak sector

- Higgs boson search in the WW channel:
 - WW cross section measurement.
 - Exclusion range: $159 < M_H < 176 \text{ GeV}$.
- Anomalous quartic gauge boson couplings:
 - First limits from the Tevatron.
- Anomalous triple gauge boson couplings:
 - Most stringent limits to date at a hadron collider.
 - Most stringent limits to date on μ_W and q_W .





Thank you for your attention!

Additional material

1 *HWW*

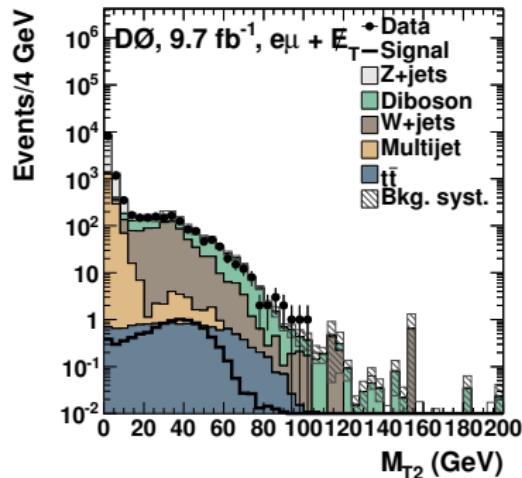
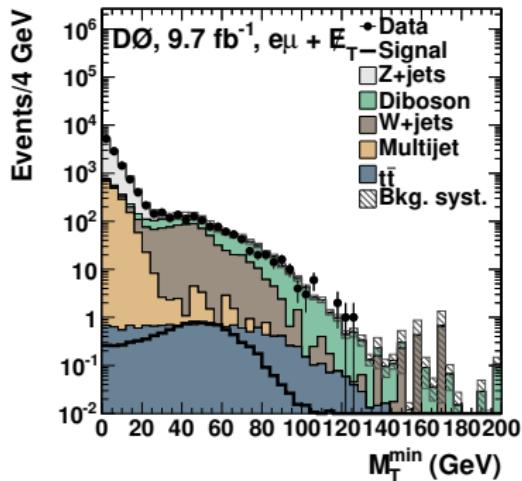
2 AQGC

3 ATGC

Z/γ^* rejection in $e\mu$

Definitions

- $M_T^{\min} = \min(M_T(e, E_T), M_T(\mu, E_T))$
 - $M_T(\ell, E_T) = \sqrt{2 p_T^\ell E_T [1 - \cos \Delta\phi(\ell, E_T)]}$
- M_{T2} : extension of the transverse mass to final states with two visible and two invisible particles (Lester and Summers, Phys.Lett. **B** 463, 99 (1999)).



Scenarios for a fourth generation of fermions

"4G-low" scenario

- $m(\ell_4) = 100 \text{ GeV}$
- $m(\nu_4) = 80 \text{ GeV}$
- $m(d_4) = 400 \text{ GeV}$
- $m(u_4) = 450 \text{ GeV}$

"4G-high" scenario

- $m(\ell_4) = 1000 \text{ GeV}$
- $m(\nu_4) = 1000 \text{ GeV}$
- $m(d_4) = 400 \text{ GeV}$
- $m(u_4) = 450 \text{ GeV}$

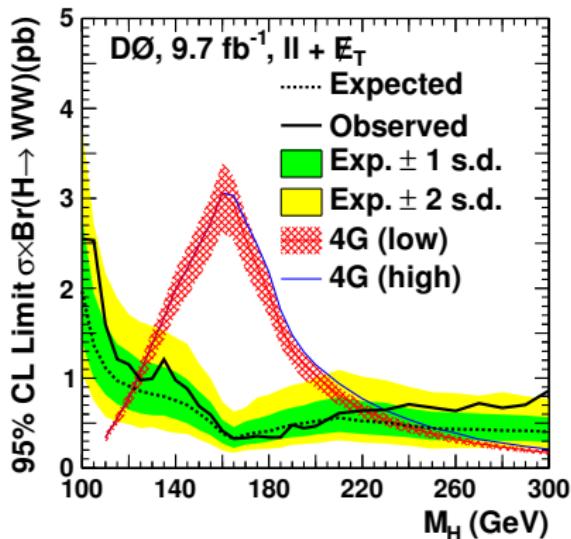
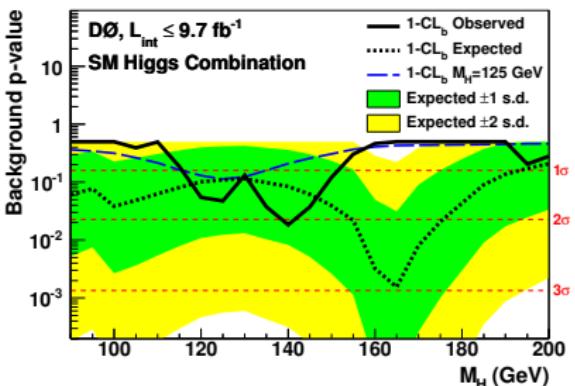
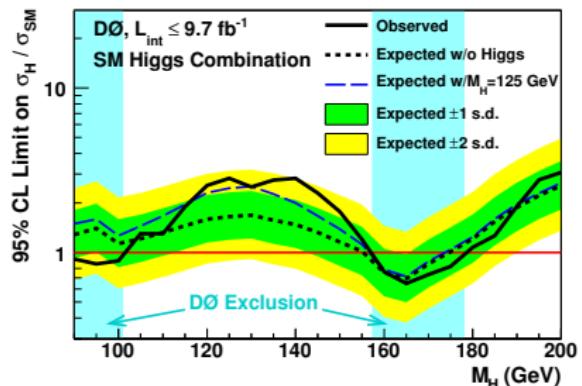
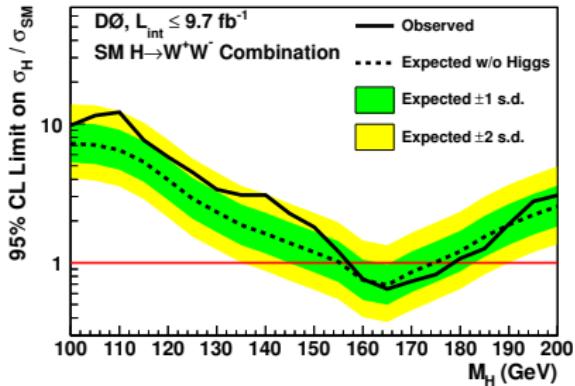
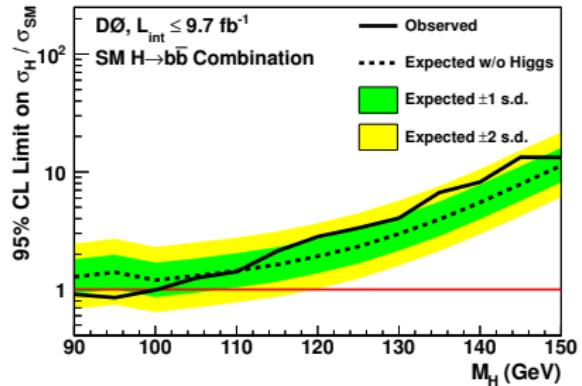


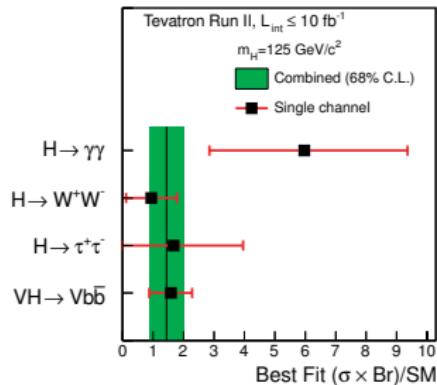
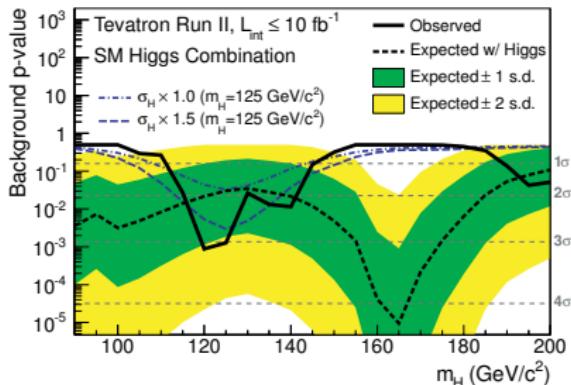
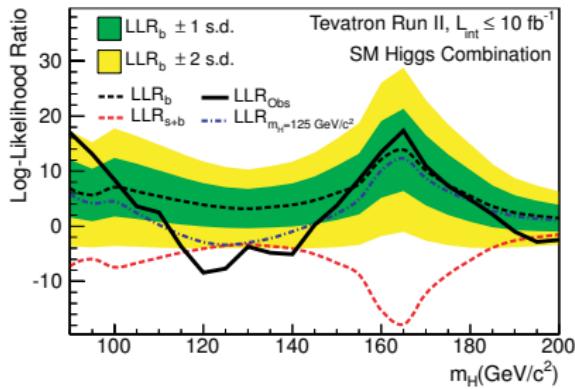
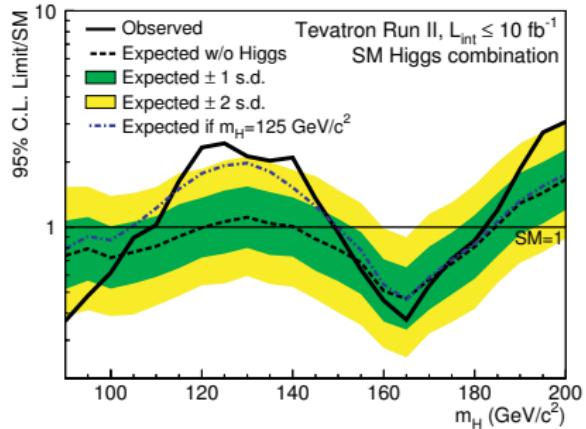
Table: Summary of systematic uncertainties (in %) for source categories. The jet, b -tagging and PDF related uncertainties are quoted for all the backgrounds combined.

Source	Uncertainty (%)
Overall normalization	4.0
W +jets normalization	6.0–50.0
Diboson cross section	6.0
$t\bar{t}$ cross section	7.0
Multijet normalization	30.0
Z +jets jet-bin normalization	2.0–15.0
$gg \rightarrow H$ cross section	7.6–35.0
VH cross section	6.0
$q\bar{q}H$ cross section	5.0
Jet energy scale	1.0–4.0
Jet resolution	1.0–3.0
Jet primary vertex association	1.0–2.0
b -tagging discriminant	1.0–2.0
PDF (background)	2.5

D0 SM Higgs combination



Tevatron combination



Anomalous quartic $WW\gamma\gamma$ and $ZZ\gamma\gamma$ gauge boson couplings

Lagrangian for anomalous quartic gauge couplings:

$$\mathcal{L}_6^0 = \frac{-e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-}_{\alpha} - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha}$$

$$\mathcal{L}_6^C = \frac{-e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^{-}_{\beta} + W^{-\alpha} W^{+}_{\beta}) - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta}$$

OPAL Collaboration (Phys. Rev. D **70**, 032005 (2004)):

$$-0.020 < a_0^W / \Lambda^2 < 0.020 \text{ GeV}^{-2}$$

$$-0.052 < a_C^W / \Lambda^2 < 0.037 \text{ GeV}^{-2}$$

$$-0.007 < a_0^Z / \Lambda^2 < 0.023 \text{ GeV}^{-2}$$

$$-0.029 < a_C^Z / \Lambda^2 < 0.029 \text{ GeV}^{-2}$$

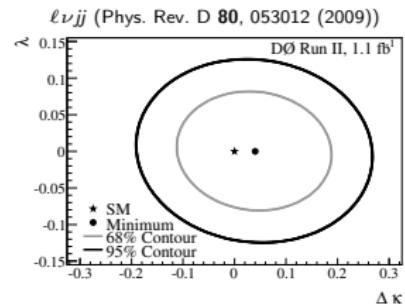
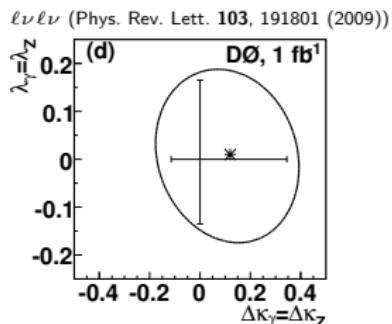
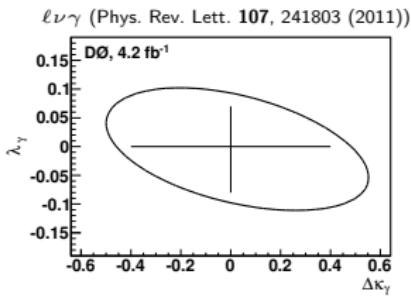
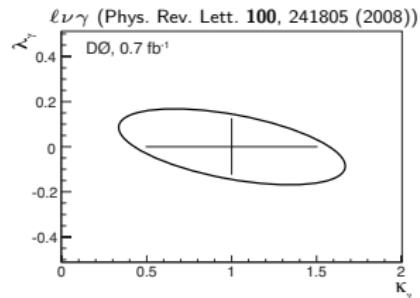
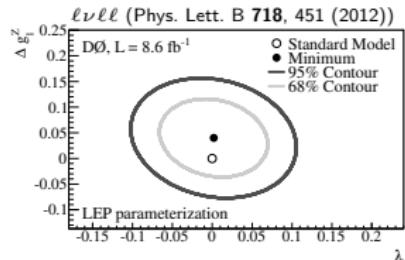
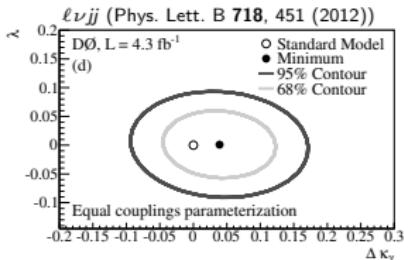
AQGC: systematic uncertainties

Source	Uncertainty (%)
$Z/\gamma^* + \text{jets}$ xsec.	6
$W + \text{jets}$ xsec.	16
diboson xsec.	6
$t\bar{t}$ xsec.	7
Multijet norm.	30
\cancel{E}_T modeling	4-5
Photon exchange and DPE norm.	100
Signal xsec.	20
Jet energy scale	4
Jet resolution	0.5
Jet identification	2
Jet association to $p\bar{p}$ vertex	2
$W + \text{jets}$ modeling	10
WW modeling	5
W, Z p_T modeling	< 1

ATGC: main systematic uncertainties

$\ell\nu jj$ (stat. dominated)	
Background cross sections	6.3 – 20%
Integrated luminosity	6.1%
Jet energy scale	3 – 9%
Jet energy resolution	1 – 10%
$\ell\ell\ell\ell$ (stat. dominated)	
Diboson p_T modeling	0.1 – 0.4%
Lepton / jet energy scale	0.2 – 6.0%
Lepton / jet resolution	1%
$\ell\ell\nu\nu$ (stat. dominated)	
Background modeling	< 7%
Integrated luminosity	6.1%
Lepton identification and trigger efficiencies	< 3%
$\ell\nu\gamma$ (syst. dominated)	
Integrated luminosity	6.1%
Lepton and photon identification	1 – 5%
Background modeling	1 – 10%
Cross sections	3 – 6%

Individual limits



Generators for ATGC signal

Channel	SM	ATGC
$WW + WZ \rightarrow \ell\nu jj$	PYTHIA reweighted to NLO (MC@NLO), full sim.	MCFM (reweighting of SM)
$WZ \rightarrow \ell\nu ll$	PYTHIA reweighted to NLO (MC@NLO), full sim.	MCFM (reweighting of SM)
$W\gamma \rightarrow \ell\nu\gamma$	BHO + PYTHIA reweighted to NLO, full sim.	BHO + PYTHIA, full sim.
$WW \rightarrow \ell\nu\ell\nu$	PYTHIA, full sim.	HWZ, fast sim.

ATGCs from CDF: WZ

Phys. Rev. D **86**, 031104 (2012).

	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta \kappa_Z$
Exp.	1.5	(-0.11, 0.12)	(-0.12, 0.23)	(-0.58, 0.94)
Obs.	1.5	(-0.09, 0.11)	(-0.09, 0.22)	(-0.42, 0.99)
Exp.	2.0	(-0.10, 0.10)	(-0.11, 0.20)	(-0.53, 0.86)
Obs.	2.0	(-0.08, 0.10)	(-0.08, 0.20)	(-0.39, 0.90)